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Lithospheric dynamics and the rapid Pliocene–Quaternary subsidence phase in the southern North Sea basin

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ABSTRACT

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We present stratigraphic modeling and quantitative analysis of the Pliocene and Quaternary subsidence of the southern North Sea basin. During the Late Pliocene, well before the onset of Quaternary glaciation, the subsidence rate in the southern part of the North Sea basin showed a ten-fold increase relative to previous Tertiary rates. The high Pliocene–Quaternary subsidence rate is consistent with the direction and state of the present intraplate stress field in Northwest Europe. One possible consequence of the modern compressional stress field in Northwest Europe is reactivation of faulting in the Central Graben resulting in localized stretching and the development of pull-apart basins. Alternatively, the acceleration in Late Pliocene subsidence rates could be due to localized flexural downwarping of the lithosphere in the Central Graben caused by an increase in the level of intraplate compression. Both mechanisms succesfully predict the major characteristics of the overall Quaternary subsidence history and stratigraphy. Gravity modeling suggests that the mechanism of localized stretching dominates the recent tectonostratigraphic evolution of the southern North Sea.

Introduction

During the Quaternary unusually rapid sedimentation occurred in the southern part of the North Sea basin, leading to sediment thicknesses which are locally up to 1000 m (Fig. 1a). In various locations the mean Quaternary sedimentation rates were about ten times as high as the mean Tertiary rate. Since most sediments were deposited in a shallow-water environment, the southern part of the North Sea basin must have experienced locally an extremely high rate of subsidence. During the Tertiary the overall development of the North Sea basin is characterized by subsidence rates which are much more in accordance with the post-rift development of rifted continental margins (Sclater and Christie, 1980; Ziegler, 1982). Although evidence exists for significant changes in sedimentation rates and the location of depocenters throughout the Cenozoic (Bjørslev Nielsen et al., 1986), quantitative subsidence modeling has shown that from Early Cretaceous time onward, the development of the North Sea is primarily the result of thermally induced subsidence caused by Late Triassic to Early Cretaceous stretching events and isostatic adjustment to sediment loading (e.g. Sclater and Christie, 1980; Barton and Wood, 1984; Thorne and Watts, 1989). Although many of these studies did note the anomalous Pliocene–Quaternary subsidence rate, they mostly did not address its origin. Exceptions are the studies by Sclater and Christie (1980) and Thorne and Watts (1989). The former authors state that "the rapid increase in sedimentary accumulation during the Pliocene through present could be the result of a shallowing depth below sea level and the high porosity of the subsurface shales". The latter study, based on a more extensive data set, attributes the anomalous Quaternary tectonic subsidence phase to thermal rejuvenation in association with a renewed rifting phase. This interpretation is primarily based on the observa-

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tion that the Quaternary depocenters coincide with earlier tectonic trends such as the West Netherlands basin, the Broad Fourteens basin and the Dutch Central Graben (compare Figs. 1a and 1b).

The transition from thermal subsidence rates to subsidence rates which require renewed tectonic activity probably occurred during the Pliocene. From Mid-Miocene time onwards a progressive

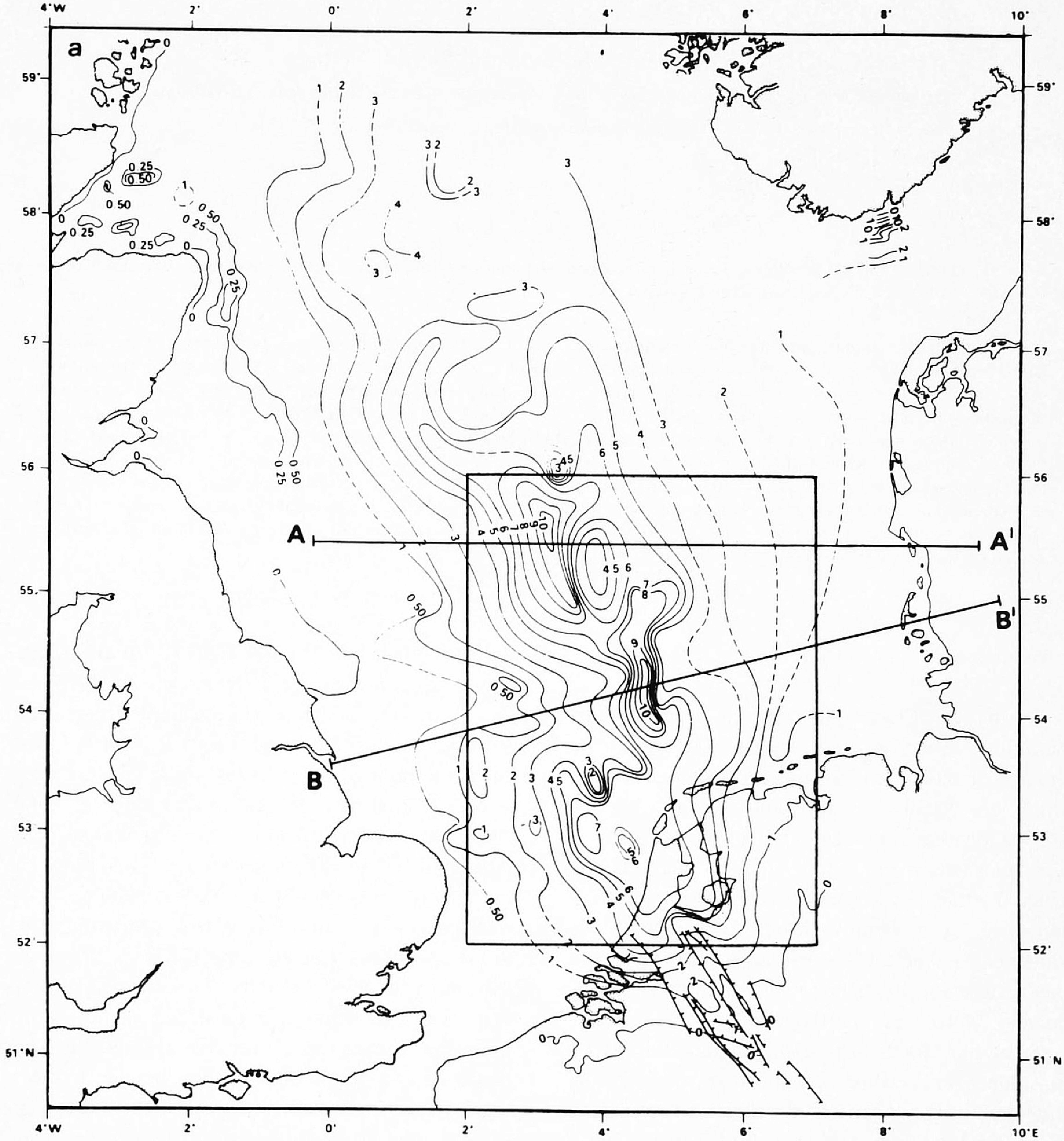

Fig. 1. (a) Isopach map of Quaternary sediments in the North Sea basin showing locally anomalous sediment thicknesses. Contours are given at intervals of 100 m. (After Caston, 1977). Lines AA' and BB' give the locations of the modeled cross sections. (b) Tectonic map of the study area indicated by the box in (a) showing fault patterns at the level of the Triassic and Jurassic strata. The location of the wells used in this study are indicated by circles and well names. Modified after Kooi and Cloetingh (1989a) and GECO Exploration Services and Alastair Beach Associates (1989).

shallowing took place in the central parts of the North Sea basin (Gradstein et al., 1988). The infill associated with this period of shallowing largely explains the Miocene and Early Pliocene sediment thickness. Therefore sedimentation during this period does not require renewed tectonic activity.

In contrast, the Quaternary evolution of the southern North Sea basin differs distinctly from the Neogene, with accumulation and subsidence patterns that began to change during the Late Pliocene as inferred from biozonation and lithostratigraphic studies (Zagwijn and Doppert, 1978). Dur-

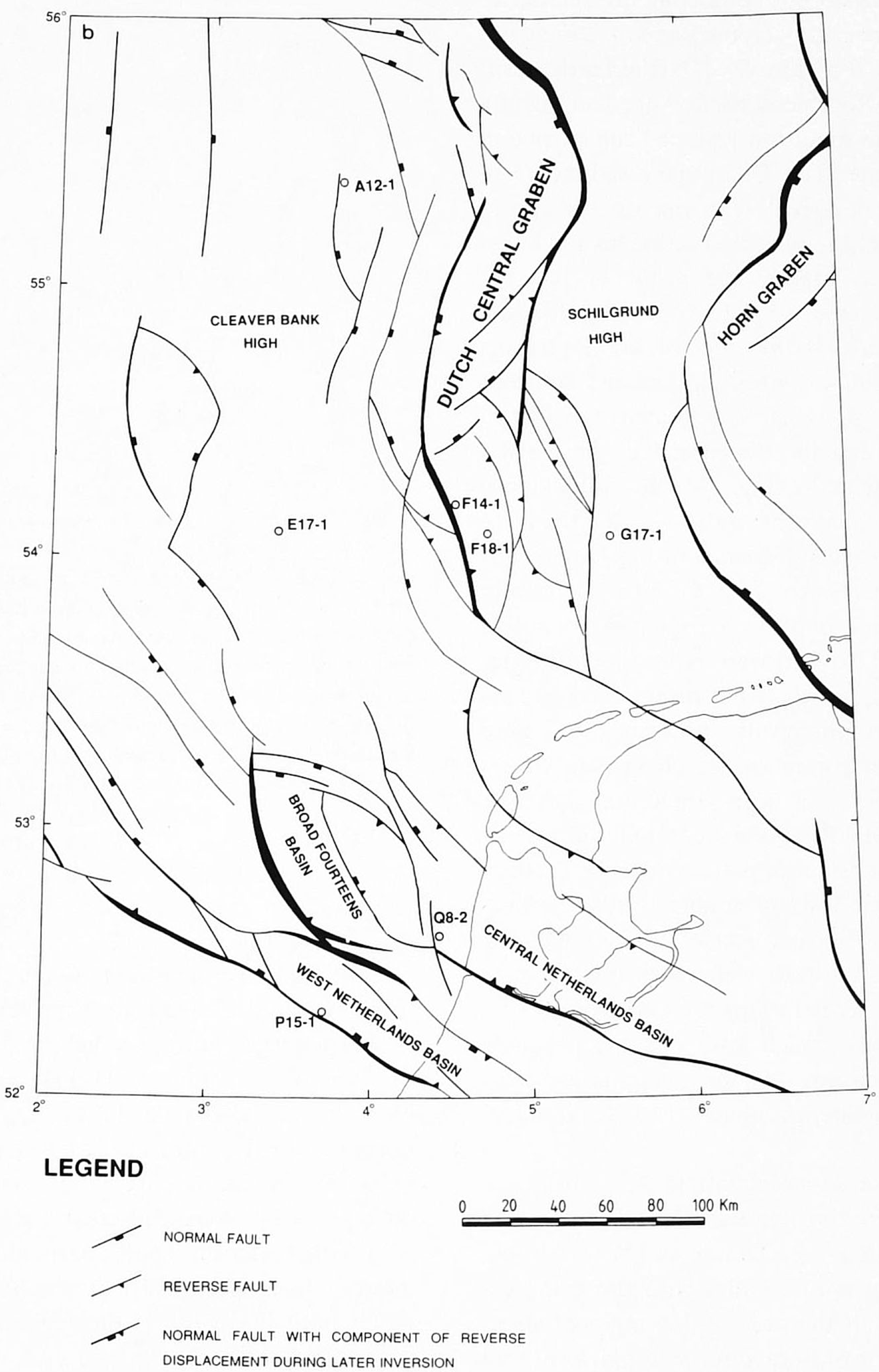

Fig. 1 (continued).

ing the Late Pliocene the delta progradation of the rivers Rhine and Meuse increased considerably. The large sediment supply to the North Sea basin is primarily associated with the deforested and permafrost conditions of western Europe. In this environment the uplifting hinterland underwent extensive erosion and many unconformities observed in the Pleistocene sediments are related to periods of increased tectonic activity (Zagwijn, 1989). Areas such as the West Netherlands basin and the Broad Fourteens basin were tectonically quiet in Miocene times but resumed subsidence in the Late Pliocene. The Quaternary sediments in these basins are of a shallow marine or continental facies. Therefore, the observed sediment thickness up to 700 m, is mainly the result of tectonic subsidence. Tectonic subsidence curves for the West Netherlands basin, the Broad Fourteens basin and the Dutch Central Graben and adjacent areas generally show an accelerated subsidence rate already during the Pliocene, well before the onset of the glaciation (Fig. 2). These subsidence curves suggest that the ratio of Tertiary to Quaternary tectonic subsidence in the Dutch part of the Central North Sea Graben is locally 240 : 300 m, which implies that Quaternary subsidence rates (100 m/Ma) were more than an order of magnitude higher than the mean Tertiary rate (about 5 m/Ma). The results shown in Fig. 2 were obtained without correction for changes in water-depth and sea-level changes. Including these effects generally yields a good fit to long-term thermally induced subsidence patterns during Tertiary times (Kooi et al., 1989). For some wells, shoaling can nullify the Pliocene acceleration of tectonic subsidence, but for most wells both the Pliocene and Quaternary accelerations remain strongly present in the curves, which attests to the probable true tectonic nature of the anomalous Plio-Quaternary sub-sidence phase (Kooi and Cloetingh, 1989b).

In general, rapid accelerations in subsidence such as discussed above are attributed to renewed phases of extension (e.g., Thorne and Watts, 1989). This explanation is in conflict with the compressional character of the present-day regional stress field in the Northwestern European platform and the North Sea basin (Klein and Barr, 1986). In the present study we investigate two possible explanations for rapid Plio-Quarternary subsidence in the North Sea area, both of which are consistent with the spatial and temporal characteristics of the Neogene and Quaternary intraplate stress field in northwestern Europe. These mechanisms both involve "reactivation" of graben structure, but in different ways: localized crustal stretching associated with strike-slip (pull-apart) and compression induced local downwarp of the lithosphere (Fig. 3). In both mechanisms the regional compressive stress field in the North Sea area plays a critical role.

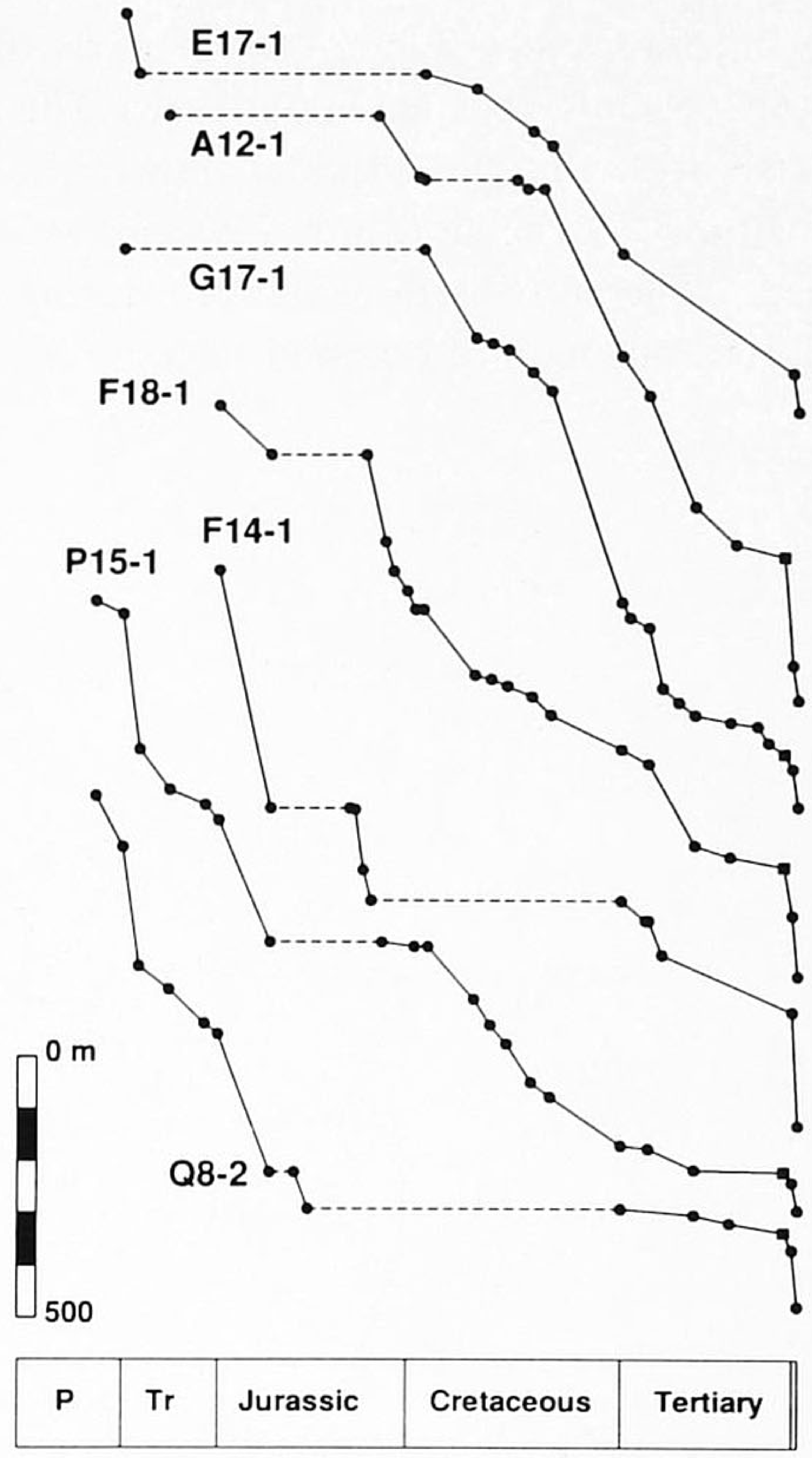

Fig. 2. Tectonic subsidence curves for wells from the West Netherlands basin, the Broad Fourteens basin and the Dutch Central Graben and surrounding areas. In the backstripping analysis, no correction for changes in water depth and sea level has been applied. The locations of the wells are indicated in Fig. 1b. Note that the anomalous subsidence rates already start during the Pliocene. The beginning of the Pliocene is indicated (where present) by a square symbol in the curves. (After Kooi et al., 1989, and Kooi and Cloetingh, 1989a.)

Changes in the regional stress field and Quaternary subsidence

Klein and Barr (1986) have compiled the orientation of the maximum horizontal principal stresses in western Europe based on in-situ stress measurements, earthquake focal plane solutions, geological stress indicators and well break-out analysis. These stress orientation data indicate a propagation of stresses away from the Alpine collision front over large distances into the platform region (Fig. 4). The compressional stresses could be a mechanical consequence of the collision of the African plate with the Eurasian plate (Letouzey, 1986; Vlaar and Cloetingh, 1984). The observed stress direction is, however, also in agreement with predictions from ridge push forces associated with spreading in the Atlantic (Zoback et al., 1989). As demonstrated by microstructural analysis of paleo-stress fields, the magnitude of the intra-plate stress field in northwestern Europe has changed considerably during the Pliocene–Quaternary in response to temporal changes in the dynamics of the Europe–Africa collision (Philip, 1987). Furthermore, worldwide changes in the stress field have occurred during Pliocene–Quaternary times due to global plate reorganizations (Pollitz, 1988). Although such major plate re-organizations generally occur with characteristic intervals of a few tens of million years, individual events, and hence the associated stress changes, occur within a few million years (Philip, 1987; Cloetingh, 1988). In previous work (Cloetingh et al., 1985; 1989; 1990) we have shown that temporal changes in the level and orientation of intraplate stresses in the lithosphere have important consequences for the subsidence history and the stratigraphic evolution of sedimentary basins. For example, short-term changes in stress levels induce short-term deviations from long-term thermal subsidence patterns, traditionally attributed to eustatic sea-level fluctuations (see also Kooi and Cloetingh, 1989a,b).

During the Quaternary, sediments accumulated in a distinct spatial pattern in the southern part of the North Sea area (Fig. 1). All deep Quaternary sub-basins have about the same dimensions (a width of 30–50 km and a length of 100–150 km). Many pull-apart basins are characterized by a fixed length to width ratio (of about 3), a feature possibly associated with coalescence of smaller basins into larger ones as slip continues (Aydin and Nur, 1982) or, alternatively, with the destruction of old basins with a larger aspect ratio due to rapidly changing tectonic stresses in strike-slip environments (Mann et al., 1983). At the same time, most sub-basins are characterized by a great depth and an elongation in a NNW–SSE direc-

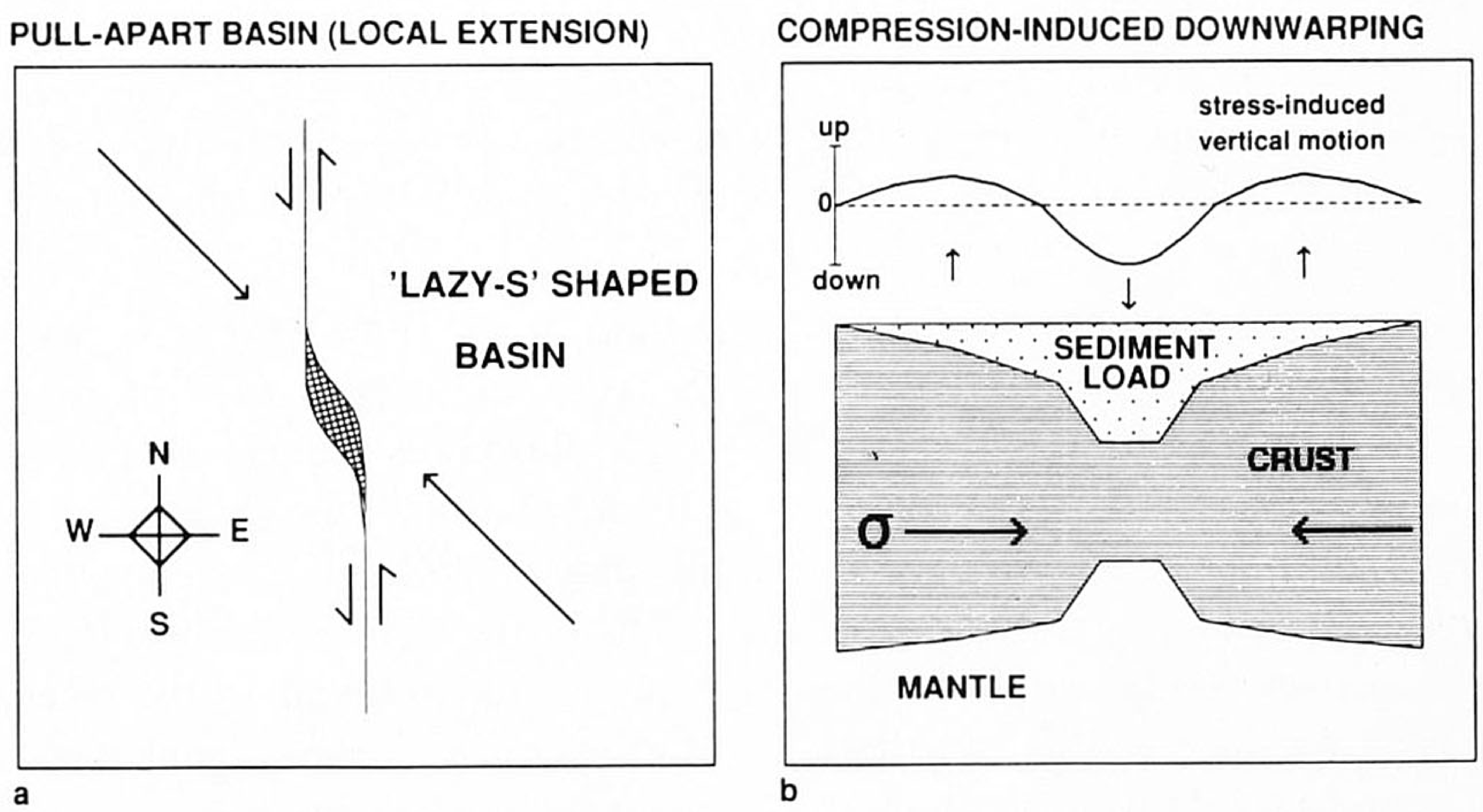

Fig. 3. Schematic illustration of the two mechanisms for the anomalous Plio-Quaternary subsidence history of the southern North Sea basin investigated in this study. (a) Reactivation of faulting in the Central Graben resulting in localized stretching and the development of pull-apart basins (modified after Mann et al., 1983). (b) Localized downwarping as a consequence of the modification of the state of flexure of the lithosphere when a change to a more compressional stress level occurs. The flexure is induced by the total sediment load in the basin (shaded); the stress-induced vertical motion is shown in the upper part of the figure.

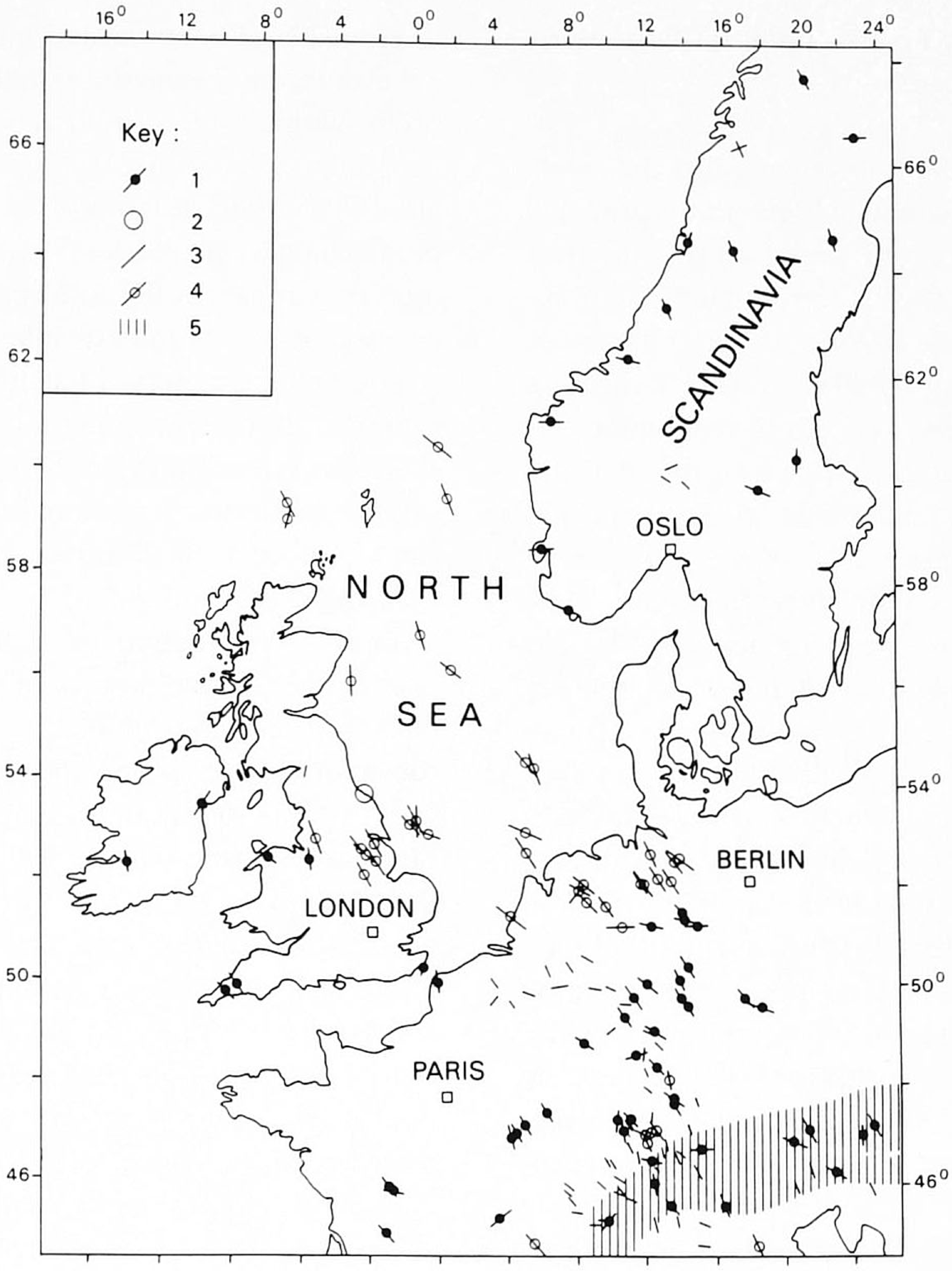

Fig. 4. Compilation of observed maximum horizontal present-day stress directions in the Northwest European Platform. *1* = the direction of maximum horizontal stress from in-situ stress measurements, *2* = a horizontal stress equal in all directions as found from in-situ stress measurements, *3* = the direction of maximum horizontal stress inferred from earthquake focal-mechanism studies, *4* = the direction of maximum horizontal stress inferred from break-out analysis, *5* = Alpine fold belt. The data indicate stress propagation away from the Alpine fold belt in the platform region. (After Klein and Barr, 1986.)

tion. These features support a pull-apart origin for the Quaternary depocenters in the southern North Sea, in particular since the present-day compressional stress field is oriented in a NW–SE direction. The maximum principal stress is oriented at an angle of about 45° from the trend of the graben bounding faults, which is favorable for the initiation of strike-slip movements. This (sinistral) strike-slip system can cause local extension at fault bends, divergent or convergent fault patterns, fault terminations and side-stepping faults (Reading, 1980). This could result in the development of "lazy s-shaped pull-apart basins" (e.g. Mann et al., 1983; Fig. 3a), with a small angle between the length axes of the basins and the strike-slip faults. This prediction is consistent with the orientation of the Quaternary sub-basins which all display an angle of about 15° relative to the faults of the Central Graben. Therefore, the stress buildup that resulted in the recent stress field in northwestern Europe could have reactivated the main faults of the southern part of the North Sea Central Graben.

The second tectonic mechanism investigated here is flexural downwarping of the lithosphere in the southern North Sea by compression. In this case, the Quaternary subsidence would be the result of lithospheric folding due to changes of the intraplate stress field coupled to the loading effect of the sediments of the North Sea basin. The mechanism is schematically outlined in Fig. 3b. When a change in intraplate stress occurs in the lithosphere, the flexural state of the lithosphere at a sedimentary basin adjusts itself to a new equilibrium, which is associated with differential vertical motions on a flexural wavelength scale (Cloetingh et al., 1985). Low levels of intraplate stress of the order of 10 MPa induce vertical motions ranging from the meter-scale to several tens of meters. On the other hand, high levels of intraplate stress, up to the total strength of the lithosphere, induce lithospheric folding (buckling) with amplitudes of the order of a kilometer and a wavelength of several tens to several hundreds of kilometers, depending of the flexural rigidity of the lithosphere (Cloetingh, 1988). Examples of lithospheric folding have been found in continental (Stephenson and Ricketts, 1990) as well as in oceanic lithosphere (McAdoo and Sandwell, 1985). For example, analysis of undulations in basement topography and geoid anomalies has demonstrated that folding of oceanic lithosphere in the Bay of Bengal has resulted from high levels of intraplate compression (Stein et al., 1989). Folding of continental lithosphere probably occurs at lower stress levels than required for oceanic lithospheric folding due to its rheological stratification (Vink et al., 1984; Kusznir and Karner, 1985; Stephenson et al., 1990; Stephenson and Cloetingh, 1991). A number of factors promote the effectiveness of compressional stresses to cause substantial downwarp in the North Sea basin. For example, the lithosphere beneath the Central Graben is characterized by values of the flexural rigidity (equivalent to an effective elastic thickness EET of 5–20 km) which are low compared to values characteristically attributed to continental lithosphere (with EET of 35 km) (Barton and Wood, 1984; Thorne and Watts, 1989). Similarly, the presence of a strongly faulted basement enhances the magnitude of stress-induced vertical motions.

In the following, we present results of stratigraphic and gravity modeling carried out to quantify the contributions of the two different mechanisms to the rapid Plio-Quaternary North Sea basin subsidence.

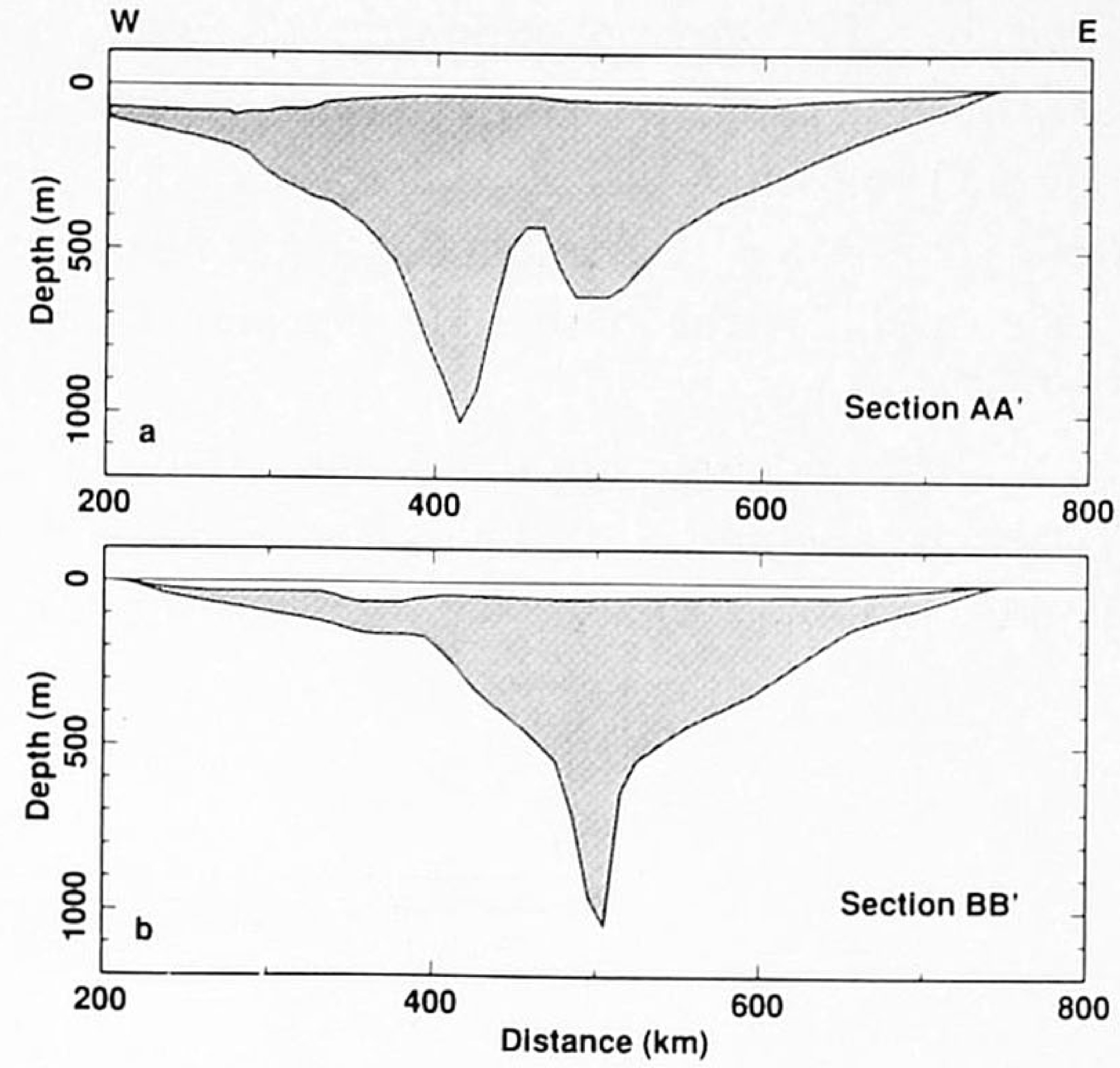

Fig. 5. Profiles showing present-day bathymetry and Quaternary sediment thickness (indicated by dark shading) for cross-section AA' (a) and cross-section BB' (b) through the southern North Sea. Locations of the two cross-sections are given in Fig. 1a.

Models for the Quaternary stratigraphy

The major Quaternary depocenters occur in the southern part of the North Sea area. We have modeled the subsidence and stratigraphic evolution using two cross sections oriented perpendicular to the main tectonic structures (Fig. 1). Structural contour maps and isopach maps (Caston, 1977; Bjørslev Nielsen et al., 1986; Kockel, 1988) were used to reconstruct the Miocene, Pliocene and Quaternary stratigraphy and the present-day bathymetry. The depth to base Miocene and the Quaternary thickness are accurately known, but information about the Pliocene thickness or the depth of the base Pliocene is sparse. Therefore, we have only modeled the Quaternary sediment thickness (Fig. 5).

Compaction of pre-Quaternary sediments contributes to the amount of space available for Quaternary sediment infill. At the same time, the pre-Quaternary sediments are also important to determine the sediment load configuration for the flexural calculations. For the northernmost section (AA') we have defined the pre-Quaternary basin

TABLE 1

Crustal stretching factors

Position (km)	Section AA'	Section BB'
365	1	1
375	1	1
385	1	1
395	1.04	1
405	1.07	1
415	1.10	1
425	1.06	1
435	1	1
445	1	1
455	1	1
465	1	1
475	1	1
485	1.015	1.03
495	1.02	1.083
505	1.02	1.1
515	1.01	1.03
525	1	1
535	1	1
545	1	1

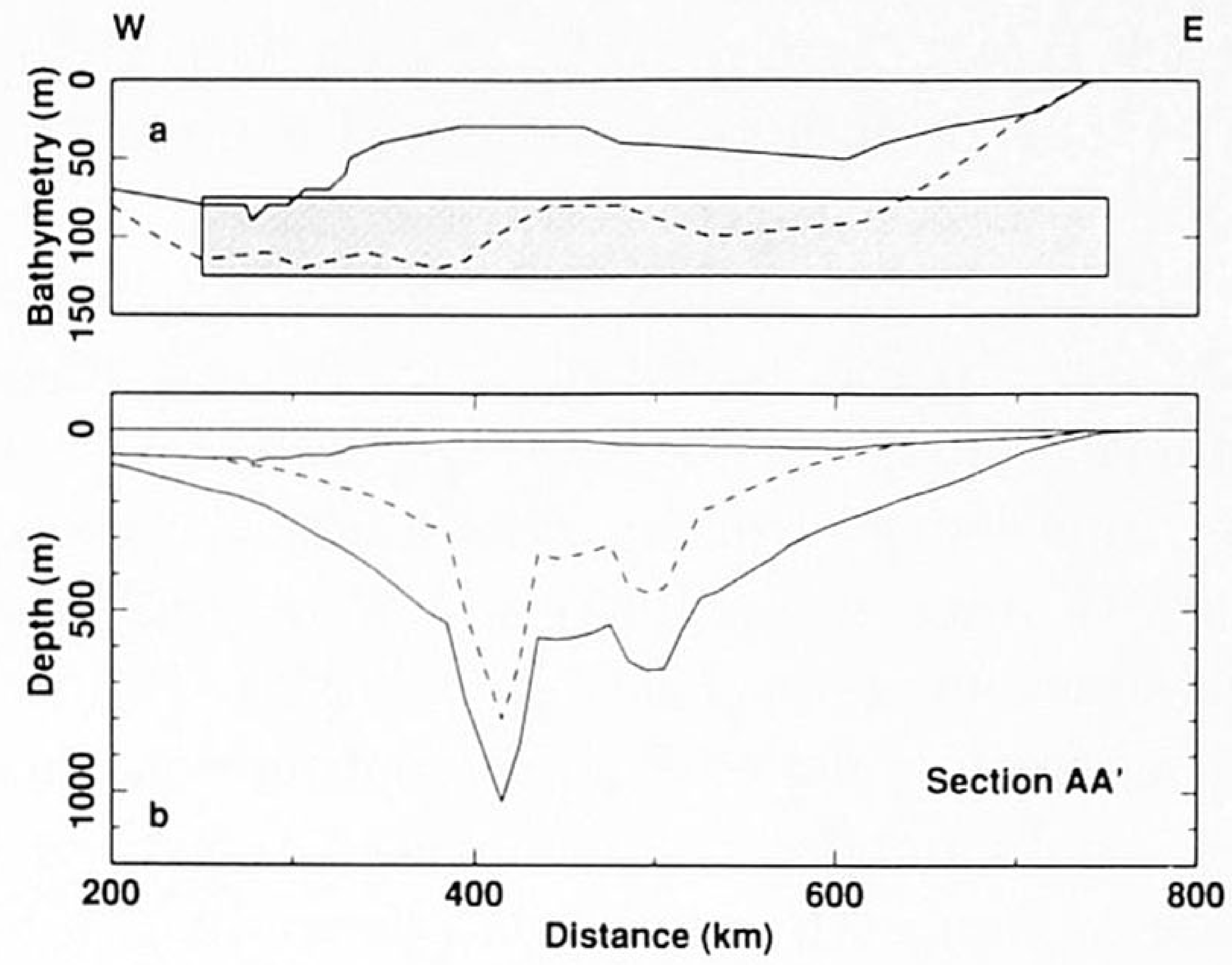

Fig. 8. Results of stratigraphic modeling for the localized crustal stretching mechanism (cross section AA'). (a) Present-day bathymetry (continuous line) and the paleo-water-depth profile inferred from the modeling (dashed line). The hatched area indicates the range of paleo-water-depths estimated from faunal analysis of well data (Gradstein et al., 1988). (b) Modeled base-Quaternary horizon for zero water-depth changes (dashed line) and for the paleo-water depth profile shown in (a).

Keen, 1980). The crustal thinning results in a rapid phase of subsidence, while the attenuation of the lower lithosphere mainly causes a perturbation of the temperature distribution, which controls the subsequent slow phase of thermal subsidence. Pull-apart basins generally show only a minor phase of thermal subsidence (Pitman and Andrews, 1985), which indicates that localized stretching occurs probably mainly in the upper part of the crust. We therefore employ only crustal stretching in the modeling. The thermal calculations are carried out using a finite difference approach (Verwer, 1977), which enables us to incorporate stretching with a finite duration and to account for lateral heat conduction. Because of the lack of stratigraphic resolution we have assumed a stretching phase of one million years (2.0–1.0 Ma) with a constant stretching rate. The crustal stretching factors used are shown in Table 1. A constant effective elastic thickness of 20 km is adopted in the flexural model.

Results of stratigraphic modeling for sections AA' and BB' are shown in Figs. 8 and 9 respectively. The contribution to the subsidence by localized stretching alone dominates the stratigraphic shape. Sediment infill in response to the change in bathymetry contributes significantly to the overall sediment thickness. For both cross-sections an excellent fit to the Quaternary stratigraphy is obtained for overall paleo-water-depths of 100 m with a maximum paleo-water-depth of 120 m. These values are in good agreement (see Figs. 8, 9) with paleo-bathymetry estimates based on faunal analysis well data (Gradstein et al., 1988).

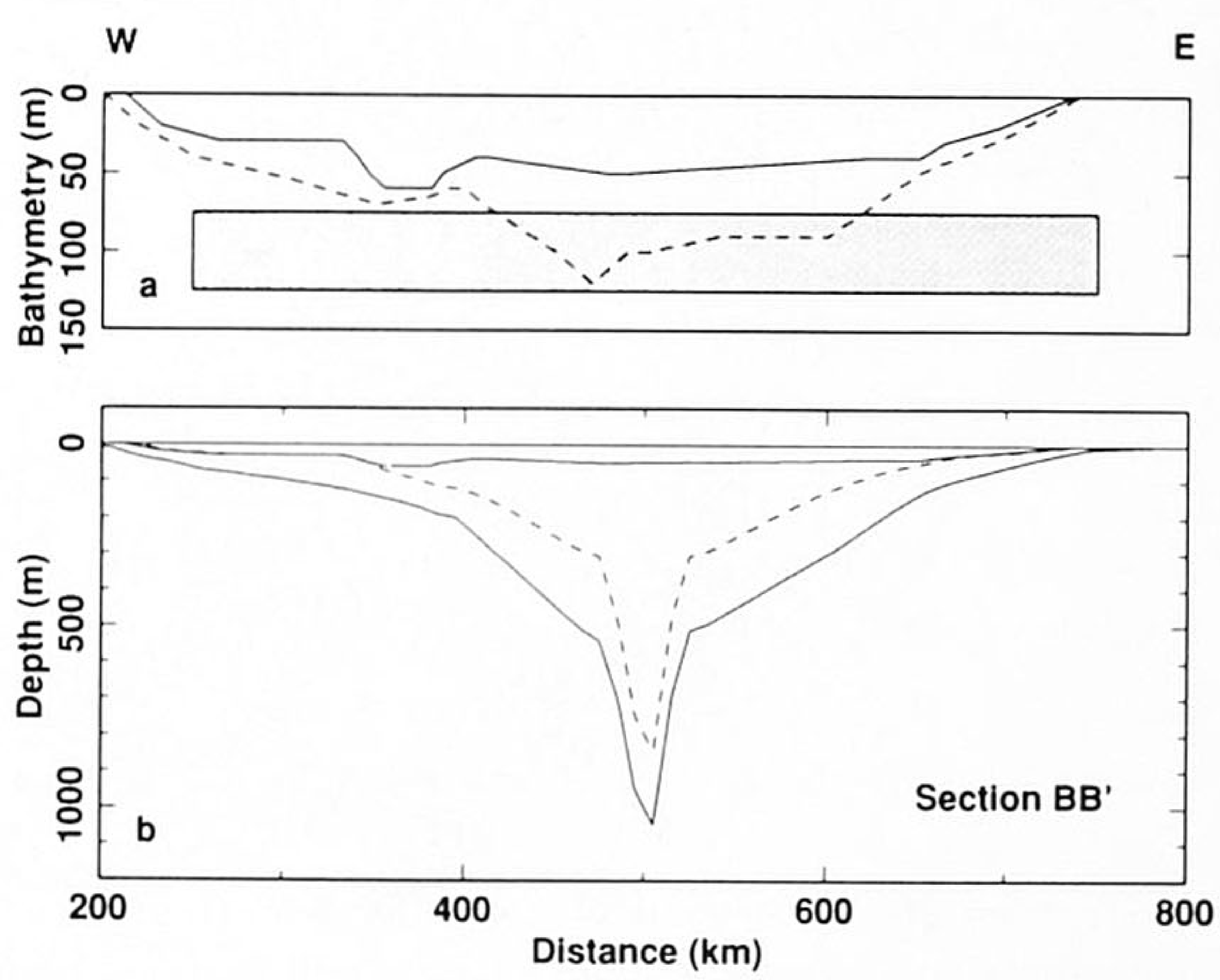

Fig. 9. Results of stratigraphic modeling for the localized crustal stretching mechanism (cross section BB'). Figure conventions as in Fig. 8.

Gravity modeling

To obtain the contribution to the gravity field of the Moho-configuration associated with the localized stretching model, firstly the Moho-configuration for the end of the Pliocene has to be reconstructed. Subsequently, this Pliocene Moho-configuration has to be corrected for the change in crustal thickness due to the Quaternary phase of localized stretching (Fig. 7). For the reconstruction of the end-Pliocene Moho we have assumed flexural compensation of the pre-Quaternary basin sediments. In the previous paragraph on Quaternary stratigraphic modeling we found an effective elastic thickness of 20 km to be consistent with the basin stratigraphy. Other workers (Barton and Wood, 1984; Zervos 1987) obtained slightly lower estimates for the North Sea basin from gravity modeling. Therefore, we have used two different elastic thickness profiles (5 and 20 km) which bound the range of observed values for the elastic properties to calculate the initial Pliocene Moho depth. Moho-depths based on refraction studies of the flanks of the central North Sea basin are characteristically of the order of 27–32 km (Sclater and Christie, 1980; Barton and Wood, 1984). We have adopted a value of 28 km as the unstretched reference thickness in the model and a density contrast between crust and mantle of 500 kg/m^3 (Zervos, 1987). The end-Pliocene crust is subsequently thinned by a factor β inferred from the stratigraphic modeling (Table 1). Estimates for crustal thicknesses and the gravity anomalies derived from the modeling using two different values for the elastic rigidity of the lithosphere are shown in Figs. 10 and 11 respectively. Both figures demonstrate a reasonable fit for the area corresponding to the deeper parts of the Quaternary basin. Therefore, local crustal stretching together with water-depth infill seems to provide a good explanation for the rapid Quaternary subsidence and the stratigraphic evolution of the North Sea area.

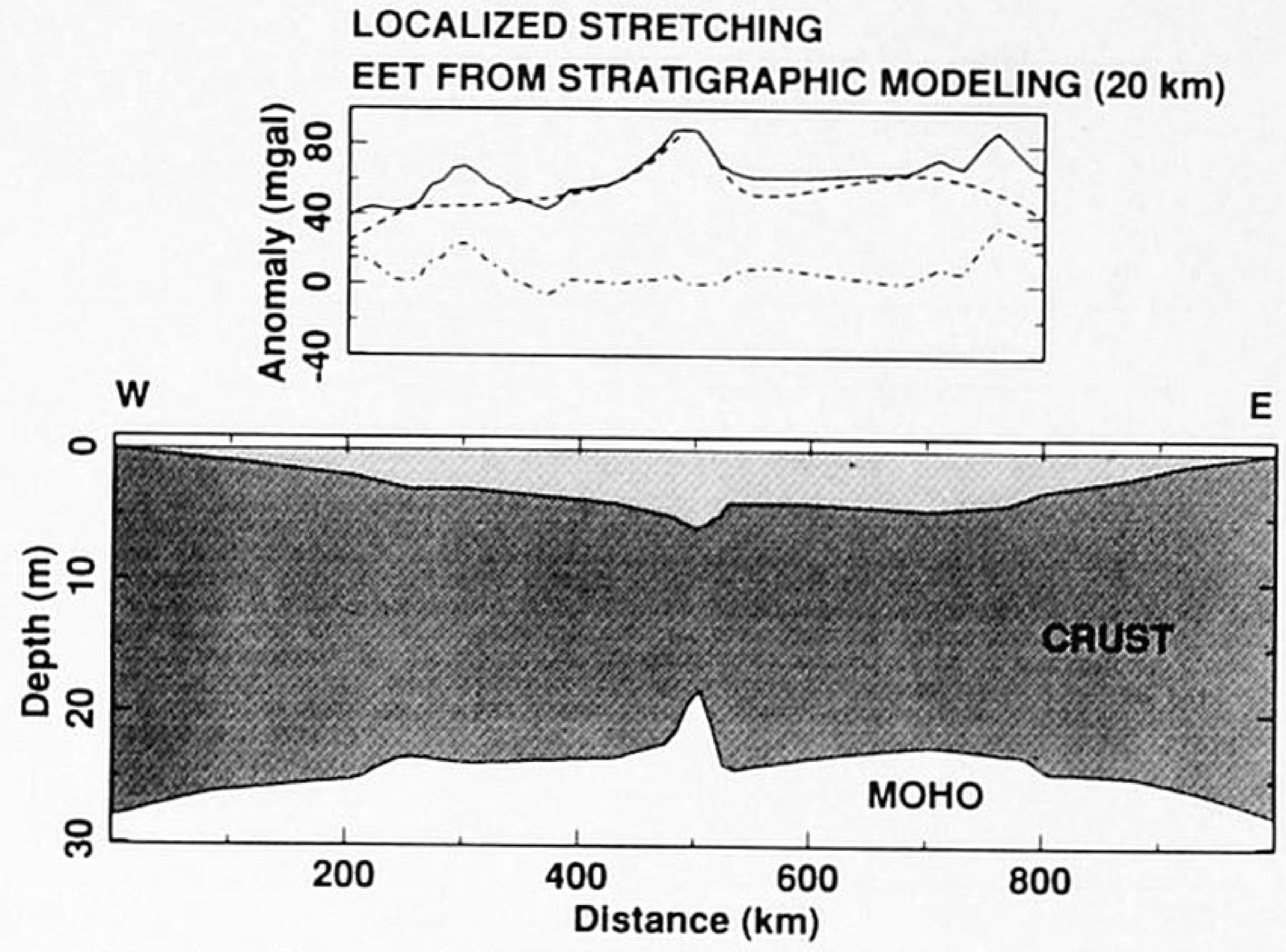

Fig. 10. Gravity modeling for the localized crustal stretching mechanism (cross-section BB'). Moho depths have been calculated for an effective elastic thickness of 20 km inferred from the stratigraphic modeling. Below: crustal configuration (indicated by dark shading) and wedge of sediments (indicated by light shading). Above: observed anomaly corrected for basin infill (continuous line), modeled anomaly (dashed line) and the residual of the two anomalies (dash-dotted line).

the vertical load acting on the lithosphere and the rheological properties of the lithosphere. Here, we adopt sediment loading only, although the isostatic forces in response to extension might also contribute to the total vertical load (Braun and Beaumont, 1989). First we tested the response of an uniform elastic plate thickness of 20 km. For this case, the model predicts that the location of the stress induced Quaternary depocenters should coincide with the position of the maximum pre-Quaternary sediment load (i.e. the deepest parts of

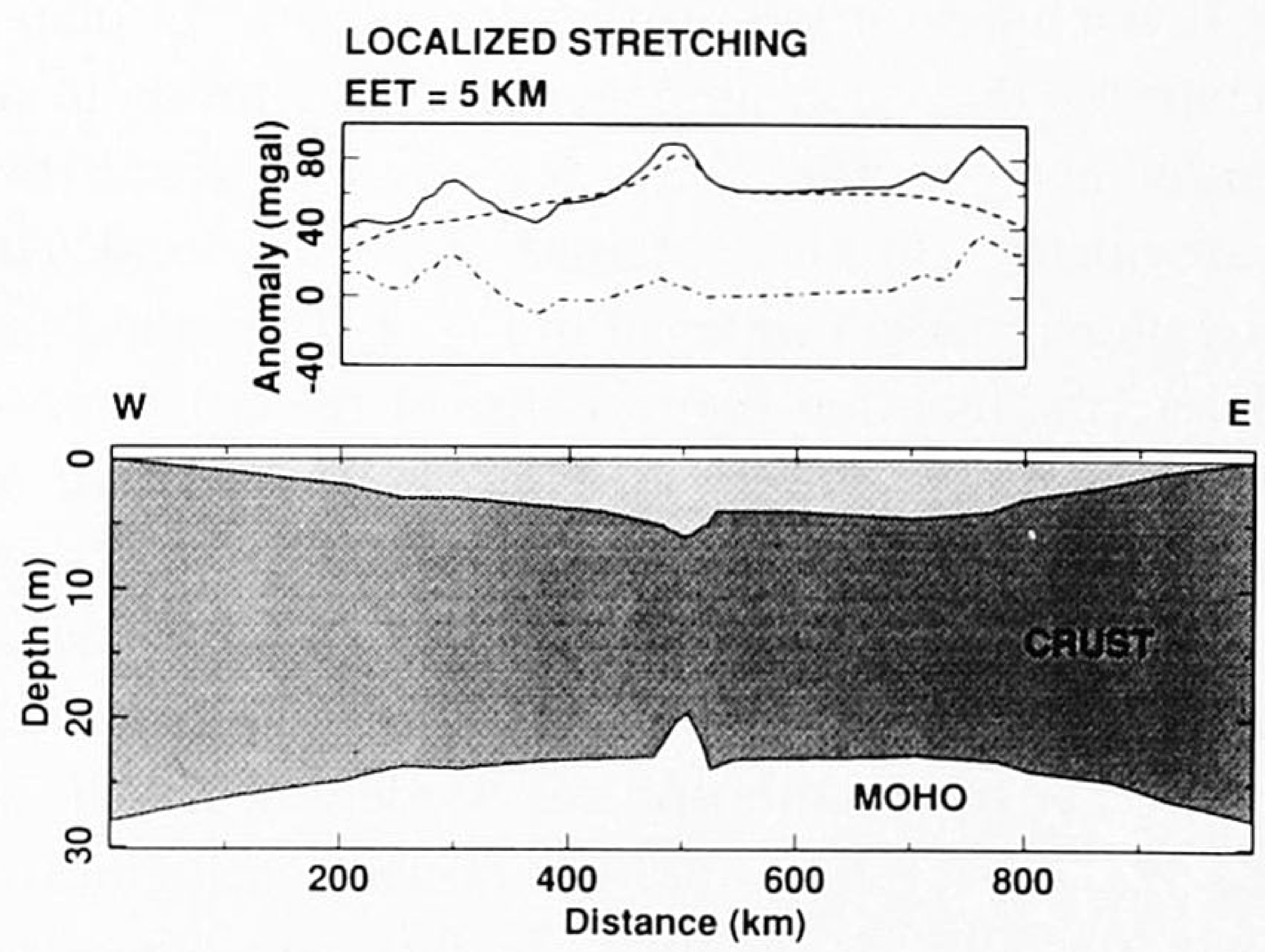

Fig. 11. Gravity modeling for the localized crustal stretching mechanism (cross-section BB'). Moho depths have been calculated for a uniform 5 km thick elastic plate model. Figure conventions as in Fig. 10.

Compressional downwarp

Stratigraphic modeling

Two main factors that control the compression induced vertical motion (deflection) of the lithosphere (Fig. 3a) are the shape and magnitude of

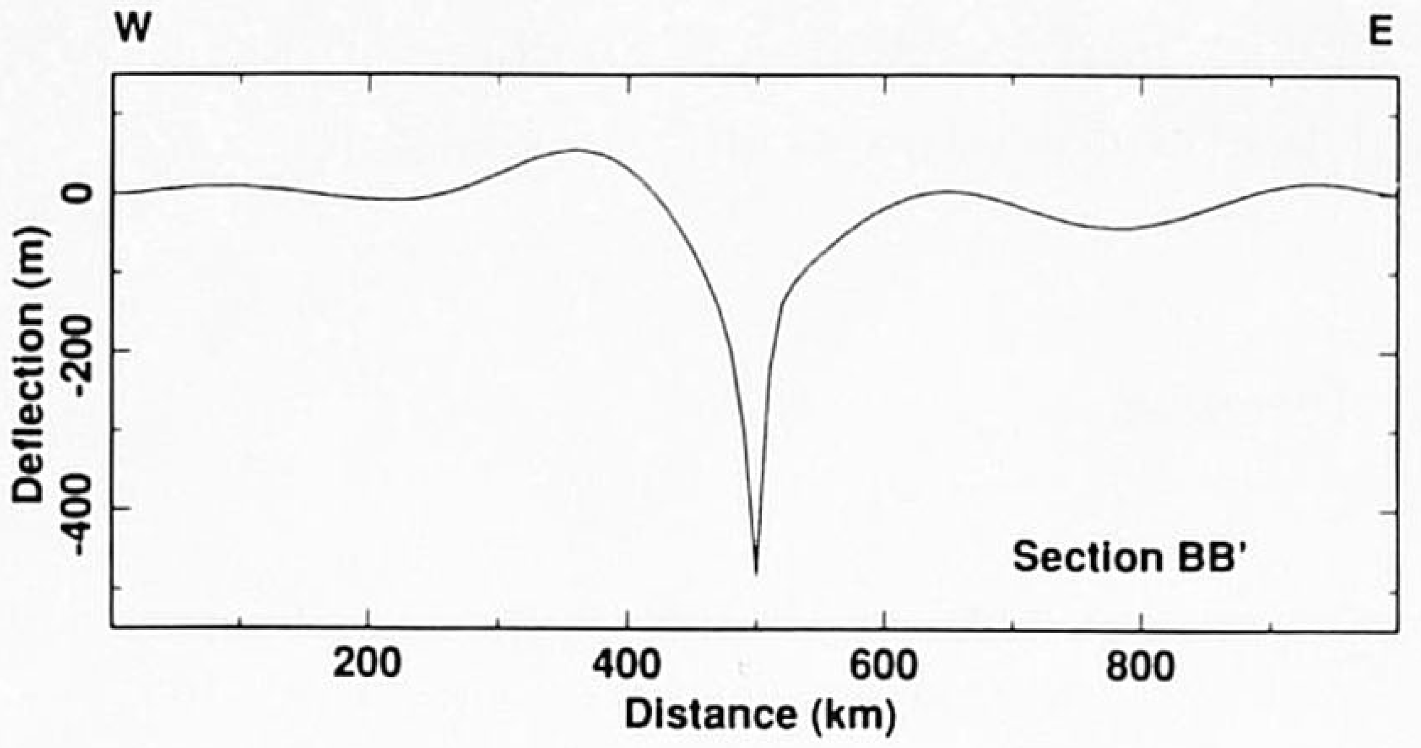

Fig. 14. Compression induced lithospheric deflection for cross-section BB' (corresponding to Fig. 13b). This deflection is superimposed on the Moho-depths calculated by regional isostatic compensation of the pre-Quaternary basin infill to yield the present-day crustal configuration. The coresponding gravity anomalies are calculated from the crustal configuration.

ness, see Fig. 13b) and a profile with a constant elastic thickness of 5 km. Subsequently, the compression induced deflection obtained from the stratigraphic modeling (Fig. 14) is superimposed on these Moho-depths. The gravity anomalies for both models are shown in Figs. 15 and 16, respectively. Comparison with the results from the localized stretching model (Figs. 10 and 11) demonstrates that the latter model produces the best fit to the gravity data in the North Sea area.

Discussion and conclusions

Stratigraphic and gravity modeling suggests that localized stretching forms the prime contributor to

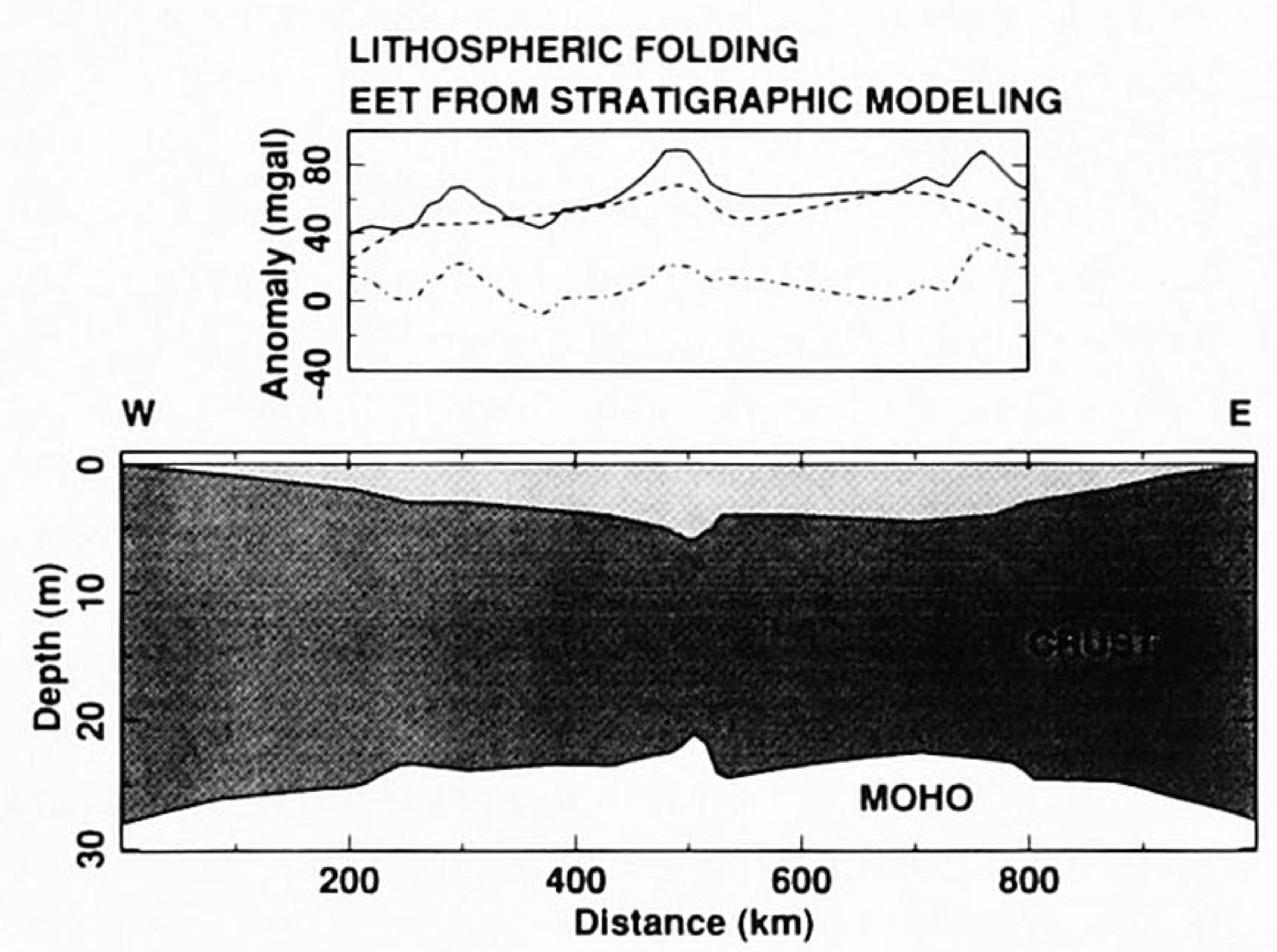

Fig. 15. Gravity modeling for compression induced lithospheric folding in the southern North Sea (cross section BB'). Moho depths have been calculated adopting the effective elastic thickness profile inferred from the stratigraphic modeling (Fig. 13b). Figure conventions as in Fig. 10.

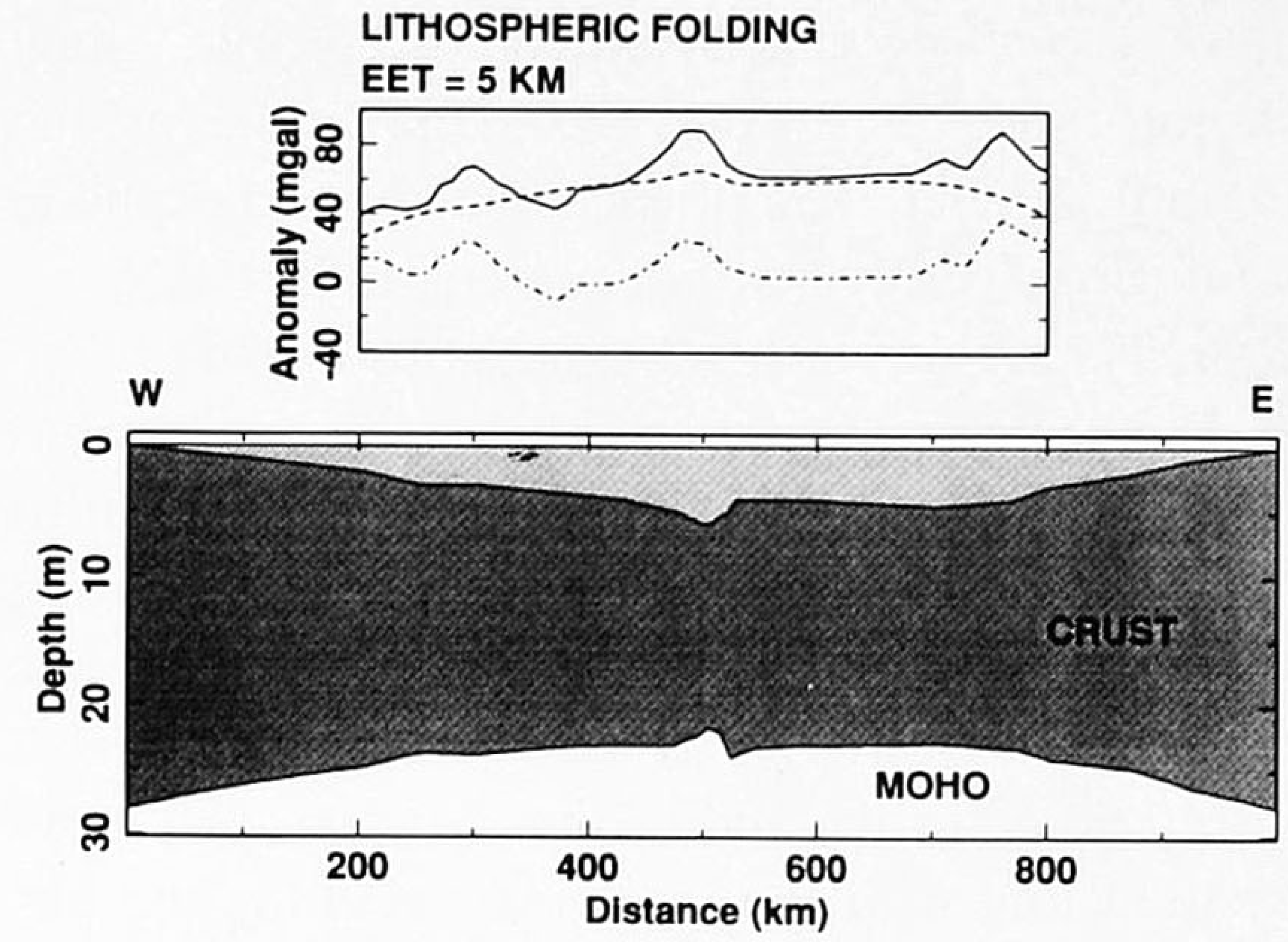

Fig. 16. Gravity modeling for compression induced lithospheric folding in the southern North Sea (cross section BB'). Moho depths have been calculated for a uniform 5 km thick elastic plate model. Figure conventions as in Fig. 10.

the rapid Quaternary subsidence in the southern North Sea basin. Such high Neogene and accelerated Quaternary subsidence rates (even up to 2000 m/Ma) have also been observed in a number of well-documented pull-apart basins (e.g., Yeats, 1978; Royden, 1985; Royden et al., 1983; Sawyer et al., 1987). Crustal extension observed at pull-apart basins can have a variety of causes (e.g., Christie-Blick and Biddle, 1985), but despite important differences in age, size, thickness of basin fill, regional setting and the cause of extension, most of these basins are quite similar in style of infilling, distribution of depositional facies and tectonic framework (Nilsen and McLaughlin, 1985). In the southern North Sea basin, local extension is probably caused by re-activated faulting in the Central Graben. This mechanism can explain the position of the depocenters along section BB' and at the east side of section AA' (Fig. 1). In a pull-apart basin, the rate of crustal thinning depends mainly on the stress magnitude and the width of the deformation zone. A narrow deformation zone enhances rapid crustal thinning and subsidence. The stratigraphic modeling described in this paper was carried out with stretching concentrated in an area roughly 40 km wide, which is consistent with the actual separation of the faults of the Central Graben (Fig. 1b).

Compression induced downwarping of the lithosphere, although to a large extent successfully explaining the overall stratigraphy, fails to pro-

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